



Life cycle assessment of biochar cofiring with coal



Yu-Fong Huang, Fu-Siang Syu, Pei-Te Chiueh*, Shang-Lien Lo

Graduate Institute of Environmental Engineering, National Taiwan University, 71 Chou-Shan Rd., Taipei 106, Taiwan

HIGHLIGHTS

- Biochar cofiring can cause lower damage to ecosystem, climate change, and resources.
- Biochar cofiring can reduce the carbon emission of thermal power plant.
- The electricity generation efficiency of cofiring is critical to reduce its impact.

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ABSTRACT

This study used life cycle assessment software SimaPro 7.2 and impact assessment model IMPACT 2002+ to evaluate the environmental impact and benefits of a biochar cofiring supply chain used for electricity generation. The biochar was assumed to be produced by rice straw torrefaction and the case study was located in Taoyuan County, Taiwan. This supply chain may provide impact reduction benefits in five categories (aquatic ecotoxicity, terrestrial ecotoxicity, land occupation, global warming, and non-renewable energy) but cause higher impacts than coal firing systems in other categories. Damage assessment of cofiring systems indicated that damage to human health was higher while the damage categories of ecosystem quality, climate change, and resources were lower. Carbon reduction could be 4.32 and 4.68 metric tons CO₂ eq/ha/yr at 10% and 20% cofiring ratios, respectively. The improvement of electricity generation efficiency of cofiring systems may be the most important factor for reducing its environmental impact.

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1. Introduction

Renewable energy has been attracting more and more interest due to concerns about limited fossil fuel supplies and increasing prices. In addition, CO₂ released by the combustion of fossil fuels is causing global warming and climate change. However, fossil fuels are still the major source of electricity and energy consumption (IEA, 2011). According to the 2008 ranking of the world's countries by fossil-fuel CO₂ emission rates provided by CDIAC, the CO₂ emission rate of Taiwan was about 11.2 metric tons of CO₂ per capita, ranked twenty-fifth in the world and first in eastern Asia (CDIAC, 2011). Therefore, issues such as developing clean, renewable energy and reducing greenhouse gas (GHG) emissions are very important for Taiwan's sustainable development. Some of the incineration plants in Taiwan are soon to be retired. In order to raise the level of consumption of renewable energy, relevant institutions plan to transform the plants into bioenergy centers that deal with biomass, such as municipal solid waste and agricultural residues (Chiueh et al., 2012).

Tilman et al. (2009) pointed out that the best biofuels should be derived from sustainable biomass feedstocks that neither compete with food crops nor directly, or indirectly, cause land clearing and that offer advantages in reducing emissions of GHG. Therefore, crop residues, double and mixed crops, sustainably harvested wood and forestry residues, perennial plants grown on degraded lands abandoned from agricultural use, and municipal and industrial solid wastes offer great potential (Tilman et al., 2009). Crop residues, including straw, stalk, husk, shell, peel and bagasse, generally have low sulfur and nitrogen content, so they are very suitable for use as feedstocks in the bioenergy supply chain.

Rice straw is a valuable biomass, not only because it is an agricultural residue, but also because it is very abundant (Shie et al., 2011). In Taiwan, the annual production of rice from 2006 to 2010 was about 1.5 million metric tons (COA, Executive Yuan, 2011). For every metric ton of grain harvested, about 1.35 metric tons of rice straw remains in the field (Kadam et al., 2000). Therefore, there is about 2 million metric tons of rice straw generated every year, so it is abundant in Taiwan. However, the cost of rice straw collection is high due to its scattered distribution. This could be a critical factor limiting the use and applications of rice straw. Traditionally, most of the rice straw left on farmland was directly

* Corresponding author. Tel.: +886 2 3366 2798; fax: +886 2 2392 8830.

E-mail address: ptchiueh@ntu.edu.tw (P.-T. Chiueh).

burned without proper disposal, causing severe air pollution, damaging scenery and wasting a source of renewable energy. After regulatory control in these years, the rice straw was either shredded and dug into the soil (80–95%) or openly burned (5–15%) (EPA, Executive Yuan, 2005). Another critical factor is the high moisture content and low heating value properties of rice straw, meaning that its direct utilization would decrease the efficiency of thermo-chemical conversion (Yaman, 2004; Bridgeman et al., 2008). In addition, lignocellulosic biomass is difficult to grind, especially when used in pulverizing systems in large-scale utility boilers for cofiring with coal (Arias et al., 2008).

Torrefaction is a mild form of pyrolysis, namely a thermo-chemical, pretreatment technology carried out in the absence of oxygen. In a torrefaction process, biomass is heated slowly (less than 50 °C/min) to 200–300 °C, and it is heated for up to 1 h. After the torrefaction process, most of the biomass remains unreacted while a small part is decomposed into volatile products that can or cannot be condensed. The remaining solid product is known as torrefied biomass or biochar. Torrefaction can improve the combustion characteristics, reduce the volume and increase the grindability of biomass (Bergman et al., 2005).

One of the potential uses of the bioenergy centers in Taiwan could be the pretreatment of rice straw by using torrefaction technology to convert it into biochar, which can then be used for electricity generation by cofiring. Therefore, a rice straw supply chain would need to be established. Such a supply chain, from rice harvesting to the conversion of rice straw into usable energy, includes several stages: collection, transport, pretreatment, storage and combustion (Chiueh et al., 2012). Each stage involves inputs and outputs of mass and energy, which may cause direct or indirect impacts on the environment. Thus, the environmental benefit and impact of the overall bioenergy supply chain should be evaluated by using the concept of life cycle assessment (LCA).

Sebastian et al. (2011) used LCA to evaluate the GHG emissions of cofiring and biomass-fired power plants, pointing out that when biomass-dedicated steam cycles had net electric efficiencies higher than 29%, approximately the same results could be attained by using either method. Lu and Zhang (2010) combined conventional process-based LCA with economic input–output LCA to evaluate the environmental and economic impacts of applying energy conversion technologies to crop residues. They found that both crop residues cofiring with coal and crop residue gasification offered greater economic scope and technical feasibility for power generation, while the return of crop residues to the fields, silo/amination and anaerobic digestion (on a household scale) offered the greatest ecological benefits (Lu and Zhang, 2010). Cherubini and Ulgiati (2010) used an LCA approach to evaluate biorefinery systems. They indicated that the use of crop residues in a biorefinery could reduce GHG emissions by about 50% and save more than 80% of non-renewable energy, but it has higher eutrophication potential than in fossil fuel systems. The eutrophication would be mostly given by nitrogen fertilization, which could cause leaching of nitrates to groundwater. Besides, the effect of land-use change can have a strong influence on the final balance of GHG emissions (Cherubini and Ulgiati, 2010).

This study used an LCA methodology to evaluate the environmental benefits and impacts of biochar produced by rice straw torrefaction and its supply chain for cofiring electricity generation.

2. Methods

This study used the IMPACT 2002+ model to acquire midpoint and damage assessment results in order to evaluate the environmental benefits and impacts of biochar production from rice straw torrefaction and its application to cofiring power generation. Ow-

ing to the lack of relevant input and output data for a full-scale rice straw torrefaction plant, reference materials were used to simulate the processes of a rice straw torrefaction plant and to model the processing outputs and pollutant emissions.

2.1. LCA method

2.1.1. Goal and scope definition

2.1.1.1. System boundary. The cradle-to-grave system boundary of a rice straw supply chain for biomass electricity generation is shown in Fig. 1. The supply chain consisted of several steps including: on-site collection, transport, torrefaction, pelletization (biochar production), storage, cofiring and land use change (caused by the removal of rice straw). Cherubini and Ulgiati (2010) pointed out that the removal of crop residues from farmland (as opposed to crop residues being returned to the soil) would decrease the level of soil organic carbon (SOC) and the SOC loss might enter the atmosphere, increasing the greenhouse effect. Since rice straw could act as an organic fertilizer, its removal might also decrease levels of soil nutrients and thus crop yields (Cherubini et al., 2009). Therefore, this study investigated the effects of land-use change caused by the removal of crop residues, including the change in GHG emission and rice straw production. The addition of chemicals to replenish soil fertility was assumed, so emissions caused by the manufacture, transport and use of these fertilizers were incorporated into the system boundary. The life cycle steps of coal (for cofiring) were also taken into account within the boundary.

To evaluate the impact reduction benefit of biomass electricity, the supply chain of coal-fired power in Taiwan was chosen as a reference system, as shown in Fig. 1. Coal mining, sea transport, storage in harbors, truck transport and combustion in power plants are included inside the system boundary.

2.1.1.2. Functional unit. To compare the potential environmental impacts of coal-fired and biochar cofiring electricity generation systems, the kilowatt hour (kWh) was chosen as the functional unit.

2.1.1.3. Case study location and assumptions. Taoyuan County was used for this case study as it has the largest rice cultivation area in northern Taiwan (31%), thereby generating the most rice straw. The incineration plant in Taoyuan County was assumed to be a bioenergy center, where rice straw is converted into biochar by torrefaction and pelletization. The biochar was assumed to be transported to the Linkou Power Plant and then co-fired with coal to generate electricity.

This study assumed that all the sub-bituminous coal used for electricity generation is obtained by import. Its lower heating value is about 25.17 MJ/kg (Grabner et al., 2010). The primary import sources include Indonesia (38.86%), Australia (35.84%), China (20.92%), Russia (2.19%), and Canada (2.01%) (BOE, MOEA, 2006). Transport of coal over long distances by sea consumes a large quantity of non-renewable energy and it is necessary to calculate the materials and energy inputs and outputs of the imported coal supply chain. Taichung Harbor was assumed to be the import harbor. Sea transport distances were calculated by using common international shipping routes between Taichung Harbor and the major harbors of the coal exporting countries. On arrival at Taichung Harbor, the coal is temporarily stored and then transported to Linkou Power Plant by trucks. This transport distance was assumed to be about 150 km.

This study assumed that rice straw biochar and coal have nearly the same grindability and thus power plants need not renew grinder equipment. However, the cofiring of biochar with coal might influence the stability of combustion flames, lowering the efficiency of electricity generation. Sebastian et al. (2011) indicated

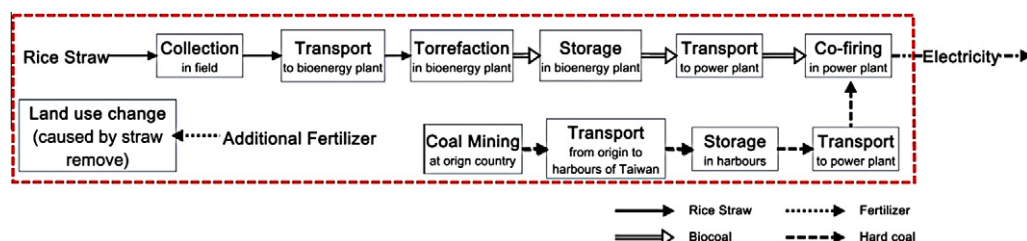


Fig. 1. The system boundary of a rice straw supply chain for biomass electricity.

that for every 10% of coal replaced by biochar (based on energy), the efficiency of electricity generation would be reduced by 1%.

2.1.2. Inventory analysis

The data for input materials, equipment and relevant emissions involve numerous issues and cannot be acquired easily, so this study primarily used the inventory data of the built-in database (Ecoinvent) of SimaPro 7.2 LCA software. Since the majority of data in the database is European, this study selected the most relevant data for each inventory stage and then modified them to reflect the actual situation in Taiwan, in order to improve the accuracy of the results. The important assumptions, data selections and relevant references for each stage of inventory analysis are described below.

2.1.2.1. Change of land use stage. As discussed in Section 2.1.1.1, the removal of rice straw might change the GHG emissions of farmland. The organic carbon content in soil could be reduced and the decreasing carbon might be released to the atmosphere. On the other hand, the organic nitrogen content in soil could be lowered, so the levels of N_2O released by denitrification might be decreased. This study assumed the total rice production to be 12,000 kg/ha/yr (from two croppings per year). Each kilogram of rice straw removed would increase GHG emissions of farmland by 1.07×10^{-1} kg CO_2 eq/yr, which is the sum of the effects of decreasing organic carbon and nitrogen content (Cherubini et al., 2009). Due to a lack of relevant information on the dosage of fertilizer required, both with and without rice straw removal, this study used dosages reported in the literature for wheat straw, as shown in Table 1. Therefore, to produce 1 kg/ha/yr of rice after the removal of rice straw, the additional N, P and K fertilizer dosages would be 1.75×10^{-3} , 9.17×10^{-4} and 7.50×10^{-4} kg, respectively. There would be various emissions after the application of N fertilizer, including volatile emission of NH_3 (10% of total N applied), direct emission of N_2O from soil (1%), nitrate released by surface runoff and eluviation (30%) and CH_4 release (1%). In addition, 1% of total NH_3 and 0.75% of total nitrate would be converted into N_2O (Cherubini et al., 2009; Cherubini and Ulgiati, 2010).

2.1.2.2. Biochar production stage. This study assumed that rice straw is treated by applying a directly-heated torrefaction process (Bergman et al., 2005). The basic devices used include a torrefaction reactor, a dryer, a boiler for the combustion of volatile gases and a pelletizer. Due to the lack of information on full-scale torrefaction

equipment, this study selected some alternative devices from the database. These included a synthetic gas plant, an industrial furnace for natural gas and a wood pelletizer, whose functions should be similar to devices used in the torrefaction process. The electricity input was assumed by using relevant inventory data for the current fuel ratios for electricity generation in Taiwan, including thermal power (75.5%), nuclear power (20.5%) and renewable energy (5%). Waste emissions in this stage, such as waste heat and flue gas, were also simulated in this study.

2.1.2.3. Coal mining stage. Since all coal used for electricity generation in Taiwan was assumed to be imported, this stage applied the coal mining inventory information from the database of the source countries, including Indonesia, Australia, China, Russia and Canada.

2.1.2.4. Storage stage. There were two types of storage involved in this stage, the storage of rice straw biochar at the bioenergy center and the storage of imported coal at the harbor. The inputs and outputs of the storage stage, including land use, electricity consumption and waste emissions, were simulated by referring to the relevant data in the database.

2.1.2.5. Transport stage. This stage included three types of transport: first, the transoceanic shipping of coal; second, the transport of fertilizer to farmland and rice straw to the bioenergy center by truck; and third, coal and biochar transport to the power plant by flatbed trucks. The inventory data of this stage took into account the input and output of the entire transportation process, including the manufacture, use, maintenance, repair and disposal of transport tools and the construction, maintenance and closure of roads.

2.1.2.6. Electricity generation stage. This study assumed that the inputs and outputs of coal-fired and cofiring electricity generation are the same (except GHG emissions). The inventory data was taken from North American Electric Reliability Corporation (NERC) data in the Ecoinvent database on sub-bituminous coal combustion in power plants. This data took combustion, cooling, interception of air pollutants (e.g., NO_x and SO_x) and ash disposal into account. CO_2 emitted by biochar combustion can be ignored as rice absorbs CO_2 from the air during its growth. However, other greenhouse gases (like N_2O and CH_4) may also be emitted and should be considered. Wihersaari (2005) reported that the GHG (including N_2O and CH_4 but excluding CO_2) equivalent emitted by the combustion of biofuels, per million joules (MJ), ranged between 0.83 and 5.6 g CO_2 eq. The average value (3.2 g CO_2 eq/MJ) was used in this study. It is generally assumed that biofuels such as forest residues do not cause any net CO_2 emissions to the atmosphere. This assumption is based on the reasoning that carbon stored in plants, which is released when burning the plant or parts of it as a biofuel, is taken up again by growing plants. Therefore, only CH_4 and N_2O released during the combustion process are here considered as GHG (Wihersaari, 2005).

Table 1
N–P–K fertilizer dosages with or without wheat straw removal (kg/ha/yr).

Fertilizer	Left in the field	Removed	Difference
N	185 ^a	206 ^b	21
P	94 ^c	105 ^c	11
K	77 ^c	86 ^c	9

^a Hamelinck et al. (2008).

^b Gabrielle and Gagnaire (2008).

^c Cherubini and Ulgiati (2010).

2.2. Simulation of rice straw torrefaction process

According to the research of Bergman et al. (2005), the technology of a directly heated, moving-bed reactor offered several advantages, such as small reactor volume and fast heating rates. Therefore, this study designed the whole process by adopting the reactor. The process included drying, torrefaction, volatiles combustion, heat exchange and cooling units. The simulation of energy flow during the biomass torrefaction process determined the quantities of biochar produced and heat wasted by calculating the energy demand and supply in the process. As to mass flow, the waste of the process was assumed to be principally boiler flue gas. This study used the results of a previous study (Syu and Chiueh, 2012), which applied chemical engineering process simulation software (ASPEN PLUS®) to simulate the composition of boiler flue gas.

3. Results and discussion

This section presents the impact assessment results for electricity generation by the cofiring of coal and rice straw biochar, in comparison with a reference system, to evaluate the environmental impact and impact reduction benefits of the technology. The extent of GHG reduction provided by biomass electricity in particular is discussed. Several key factors affecting the assessment results, as determined by a sensitivity analysis, are indicated and discussed at the end.

3.1. Potential environmental impact and impact reduction

This study assumed that part of the coal is substituted with biochar to undergo cofiring electricity generation. Table 2 lists the potential environmental impact and impact reduction results per kWh electricity generated of two cofiring ratios (10% and 20%). The majority of categories had higher impact characterization values at the higher cofiring ratio, with the exception of aquatic ecotoxicity, terrestrial ecotoxicity, land utilisation, global warming and the use of non-renewable energy.

The heating value of biochar was lower than coal, so more biochar would be required to generate the same amount of electricity. Therefore, power plants would produce more ash and waste at higher cofiring ratios. This study assumed that the production of ash and air pollutants from the combustion of biomass and coal, per unit, are the same. The emission of air pollutants (e.g., polycyclic aromatic

hydrocarbons (PAHs) and dioxins) and heavy metals in wastewater (caused by the treatment of ash) may be greater, since the feeding quantity of biochar would be higher than that of coal to generate the same electricity. The higher feeding quantity would result in larger combustion devices, which would require more steel for construction. According to the heating values and bulk densities of biochar and coal, the combustion device could be increased by about 15% and 30% at the cofiring ratios of 10% and 20%, respectively. This could cause the increase of carcinogen emissions via the steel refining process. In addition, higher cofiring ratios increased the demand for biochar and therefore, the inputs and outputs of the biochar life cycle, including additional fertilizers and electricity. The increments of biochar life cycle inputs and outputs would result in higher characterization values of carcinogens, non-carcinogens, respiratory organics/inorganics, terrestrial acidification, aquatic acidification, and mineral extraction categories with higher cofiring ratios. The additional fertilizers, due to the removal of rice straw, would lead to increased phosphate emissions from the manufacturing process. Thus, the usage of biochar might increase the impact on aquatic eutrophication. At the 20% cofiring ratio, the aquatic eutrophication impact was about 16 times higher than that of coal-fired electricity. In Taiwan, about 20% of electricity is generated from nuclear power. Therefore, the increased electricity consumption of biochar production may indirectly raise the environmental impact of ionizing radiations.

According to the inventory data and characterization results, the primary substance affecting aquatic and terrestrial ecotoxicities was aluminum emitted by explosive demolition during coal mining. The aluminum was emitted into the air and then deposited on surface ground and water. Increased cofiring ratios would contribute to a decrease in coal usage and aluminum emissions. Moreover, rice absorbed CO₂ during its growth, so this absorption could offset the CO₂ emissions resulting from its combustion. The higher cofiring ratio meant that more biochar replaced coal, lessening the impact on global warming and decreasing the use of non-renewable energy.

In the characterization results, a rice straw cofiring system provided positive environmental benefits in five impact categories (Table 2). Table 3 shows damage assessments transformed from these characterization values. Compared with the reference system, only human health damage was higher with the cofiring system, while damage in the other three categories (ecosystem quality, climate change and resources) was lower. The higher human health damage of the cofiring system came from the higher potential

Table 2

The potential environmental impact and impact reduction per kWh electricity generated by 10% and 20% cofiring.

Impact category	Unit	10%	Variation ^a (%)	20%	Variation ^a (%)	Reference system
Carcinogens	kg C ₂ H ₃ Cl eq	2.86E-03	5.27	3.01E-03	10.79	2.72E-03
Non-carcinogens	kg C ₂ H ₃ Cl eq	1.58E-02	3.11	1.63E-02	6.37	1.53E-02
Respiratory inorganics	kg PM _{2.5} eq	6.18E-04	2.63	6.34E-04	5.29	6.02E-04
Ionizing radiations	Bq C-14 eq	1.94E+00	55.49	2.68E+00	114.81	1.25E+00
Ozone layer depletion	kg CFC-11 eq	8.76E-09	7.37	9.40E-09	15.21	8.16E-09
Respiratory organics	kg C ₂ H ₄ eq	5.93E-05	2.87	6.10E-05	5.82	5.76E-05
Aquatic ecotoxicity	kg TEG water eq ^b	4.21E+01	−2.35	4.11E+01	−4.67	4.31E+01
Terrestrial ecotoxicity	kg TEG soil eq ^b	9.20E+00	−2.52	8.94E+00	−5.28	9.44E+00
Terrestrial acidification/nutrition	kg SO ₂ eq	1.67E-02	4.43	1.75E-02	9.43	1.60E-02
Land occupation	m ² org.arable ^c	3.85E-03	−3.85	3.68E-03	−8.10	4.00E-03
Aquatic acidification	kg SO ₂ eq	4.37E-03	3.66	4.54E-03	7.69	4.22E-03
Aquatic eutrophication	kg PO ₄ P-lim ^d	2.82E-05	792.31	5.46E-05	1627.66	3.16E-06
Global warming	kg CO ₂ eq	1.04E+00	−4.10	9.90E-01	−8.71	1.08E+00
Non-renewable energy	MJ primary	9.92E+00	−3.89	9.50E+00	−7.96	1.03E+01
Mineral extraction	MJ surplus	1.21E-03	12.01	1.35E-03	24.97	1.08E-03

^a The increase or reduction of environmental impact compared with the reference system (electricity generation only by coal).

^b TEG water/soil: triethylene glycol into water/soil.

^c Org.arable: organic arable land.

^d P-lim: into a phosphorus-limited land.

Table 3

The damage assessments and total impact single scores per kWh electricity generated by 10% and 20% cofiring.

Damage category	Unit	10%	Variation ^a (%)	20%	Variation ^a (%)	Reference system
Human health	DALY ^b	4.85E-07	2.69	4.99E-07	5.55	4.72E-07
Ecosystem quality	PDF*m ^b *yr ^c	9.65E-02	−1.36	9.51E-02	−2.81	9.78E-02
Climate change	kg CO ₂ eq	1.04E + 00	−4.23	9.90E-01	−8.70	1.08E + 00
Resources	MJ primary	9.92E + 00	−3.88	9.50E + 00	−7.98	1.03E + 01
Total point ^d	pt	2.46E-04		2.40E-04		2.51E-04

^a The increase or reduction of environmental impact compared with the reference system (electricity generation only by coal).^b DALY: disability adjusted life years.^c PDF: potentially disappeared fraction of plant species.^d The total impact single scores of the normalized and weighted damage assessments.**Table 4**

The GHG reduction of electricity generation by applying 10% and 20% biochar cofiring.

Unit	10%	20%
kg CO ₂ eq/k Wh	0.04	0.09
kg CO ₂ eq/kg rice straw ^a	0.36	0.39
Metric tons CO ₂ eq/ha/yr ^b	4.32	4.68

^a Wet rice straw (20% moisture content).^b Rice production: 12,000 kg/ha/yr.

environmental impacts in the midpoint categories of carcinogens, non-carcinogens, respiratory organics/inorganics, ionizing radiations, and ozone layer depletion. The reduction of damage caused by the biochar cofiring system increased with increasing cofiring ratios. Table 3 also lists the total impact single scores at the two cofiring ratios, which were calculated from the sum of normalized and weighted characterization values and by using the built-in normalizing and weighting factors in the model. The scores for both cofiring ratios were lower than that of the reference system, so the total environmental impact of the cofiring system should be lower. The weights of some factors can be adjusted according to specific purposes or expert comments. Therefore, a more practical and reliable result could be obtained to serve as a reference for decision makers or even to persuade them.

3.2. GHG reduction

One of the principal reasons for considering biochar for cofiring electricity generation is to abate the carbon emissions of thermal power. Table 4 shows the simulated carbon reduction of electricity generation by rice straw biochar cofiring compared with coal firing. The carbon reduction could be 0.04 and 0.09 kg CO₂ eq per kWh electricity generated and 0.36 and 0.39 kg CO₂ eq per kg rice straw at 10% and 20% cofiring ratios, respectively. Using the assumption of 12,000 kg of rice production per ha per year, the carbon reduction could be 4.32 and 4.68 metric tons CO₂ eq/ha/yr at 10% and 20% cofiring ratios, respectively. Decision makers can evaluate the benefits of carbon reduction from biochar cofiring and

compare them with other land uses by using the methods in this study.

3.3. Sensitivity analysis

In the sensitivity analysis, five variables were selected and analyzed due to their reference data with higher uncertainty or research assumptions, including: the electricity consumption of biochar production, GHG emissions from fields and additional fertilizer use due to rice straw removal, the decrease of electricity generation due to biochar cofiring and GHG emissions from biochar combustion. Table 5 lists the changes in total impact single scores (compared with the original values) in the sensitivity scenarios of the original cofiring ratio (20%) and $\pm 25\%$ and $\pm 50\%$ of the ratio.

The sensitivities to the changes of biochar cofiring ratios of the five variables were in the following order (from high to low): the decrease of electricity generation efficiency, electricity consumption, GHG emissions from fields, additional fertilizer use and GHG emissions from biochar combustion. Since the GHG emissions from biochar combustion may be offset by CO₂ absorption during rice growth, the influence of this variable on the total impact could be very small. To lower the environmental impact of the bioenergy supply chain, several strategies might be implemented, such as improving the electricity generation efficiency of biochar cofiring and increasing the energy density of biochar.

4. Conclusions

The biochar cofiring supply chain for electricity generation could provide impact reduction benefits in five categories, including aquatic ecotoxicity, terrestrial ecotoxicity, land occupation, global warming, and non-renewable energy, but it might cause higher impacts than coal firing systems in other categories. Damage assessment of cofiring systems indicated that only damage to human health showed an increase, while ecosystem quality, climate change, and resources showed a decreased likelihood of damage. Biochar cofiring may be helpful in reducing the carbon emissions

Table 5

The changes of total impact single scores in different sensitivity scenarios.

The total impact single score of original case: 2.40E-04 ^a					
Scenario (%)	Electricity consumption (%)	GHG emissions from field ^b (%)	Electricity generation efficiency decrease (%)	Additional fertilizer use ^b (%)	GHG emissions from biochar combustion (%)
−50	−2.09	−0.52	−2.86	−0.50	0 ^c
−25	−1.05	−0.26	−1.45	−0.25	0 ^c
+25	+1.05	+0.26	+1.49	+0.25	0 ^c
+50	+2.09	−0.52	+3.03	+0.50	0 ^c

^a At 20% cofiring ratio.^b Due to rice straw removal.^c Less than 0.0001%.

of power plants. The environmental impacts of biochar could be lowered by increasing its energy density and cofiring efficiency.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.biortech.2012.12.123>.

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